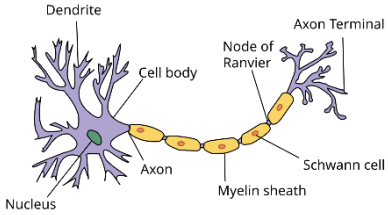
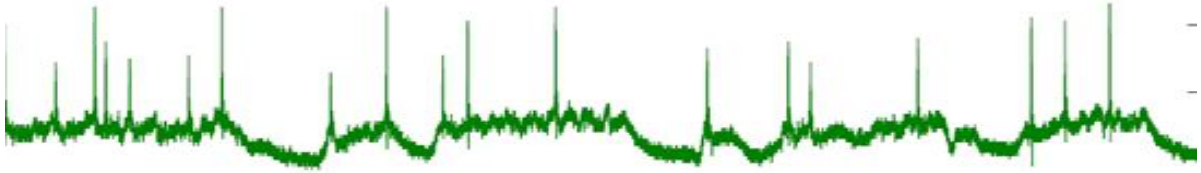




Neural coding of subthreshold sinusoidal inputs into symbolic temporal spike patterns

M. Masoliver, B.R.R. Boaretto, J. Tiana-Alsina, Cristina Masoller
Departament de Física
Universitat Politecnica de Catalunya

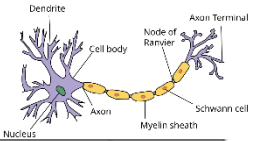
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

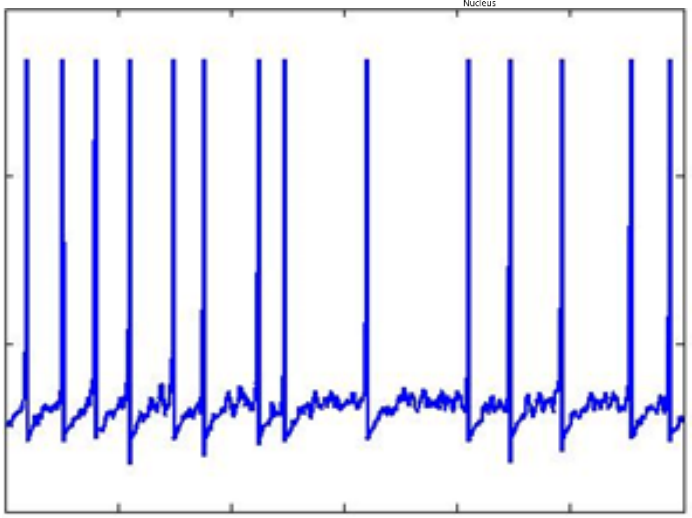
Campus d'Excel·lència Internacional

Collective Dynamics and Information Processing in Neural Systems
European Center of Living Technology, Venezia, Italy, July 1, 2025

ICREA AGAUR GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Intensity emitted by a diode laser and simulated spikes

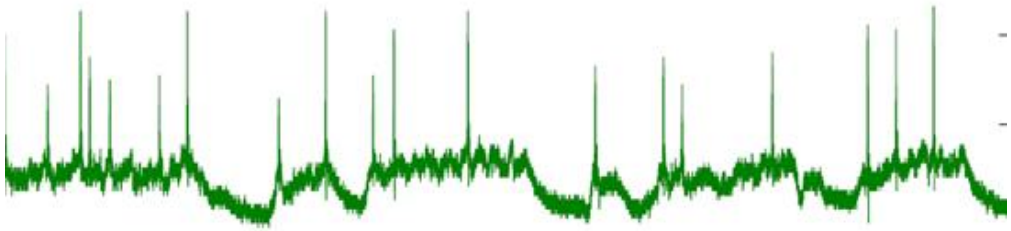




Time 10^{-9} s

Time 10^{-3} s

How neurons encode information?



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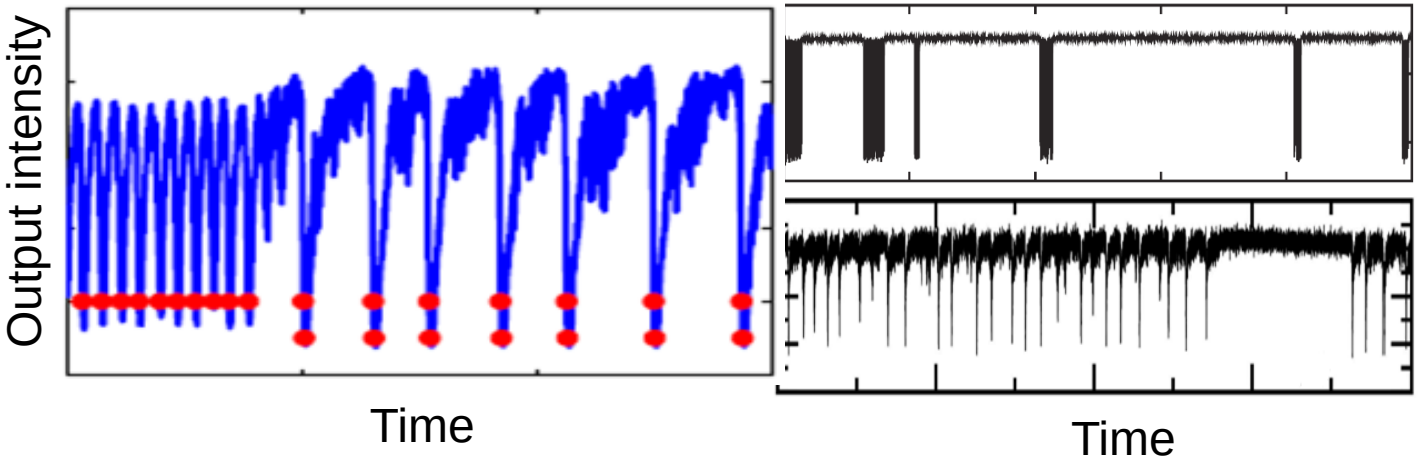
Uncovering similarities between neuron and lasers… Interesting but relevant?

- Data centers, AI and HPC systems consume a lot of power.
- Big concern in the context of climate change.
- The human brain works with only 20 Watts.
- **Laser-based neurons** should work as neurons, but
  - Much faster
  - With much less energy consumption.



Statistically similar to neurons?

A. Aragoneses et al., Sci. Rep. **4**, 4696 (2014).
C. Quintero-Quiroz et al., Sci. Rep. **6** 37510 (2016).

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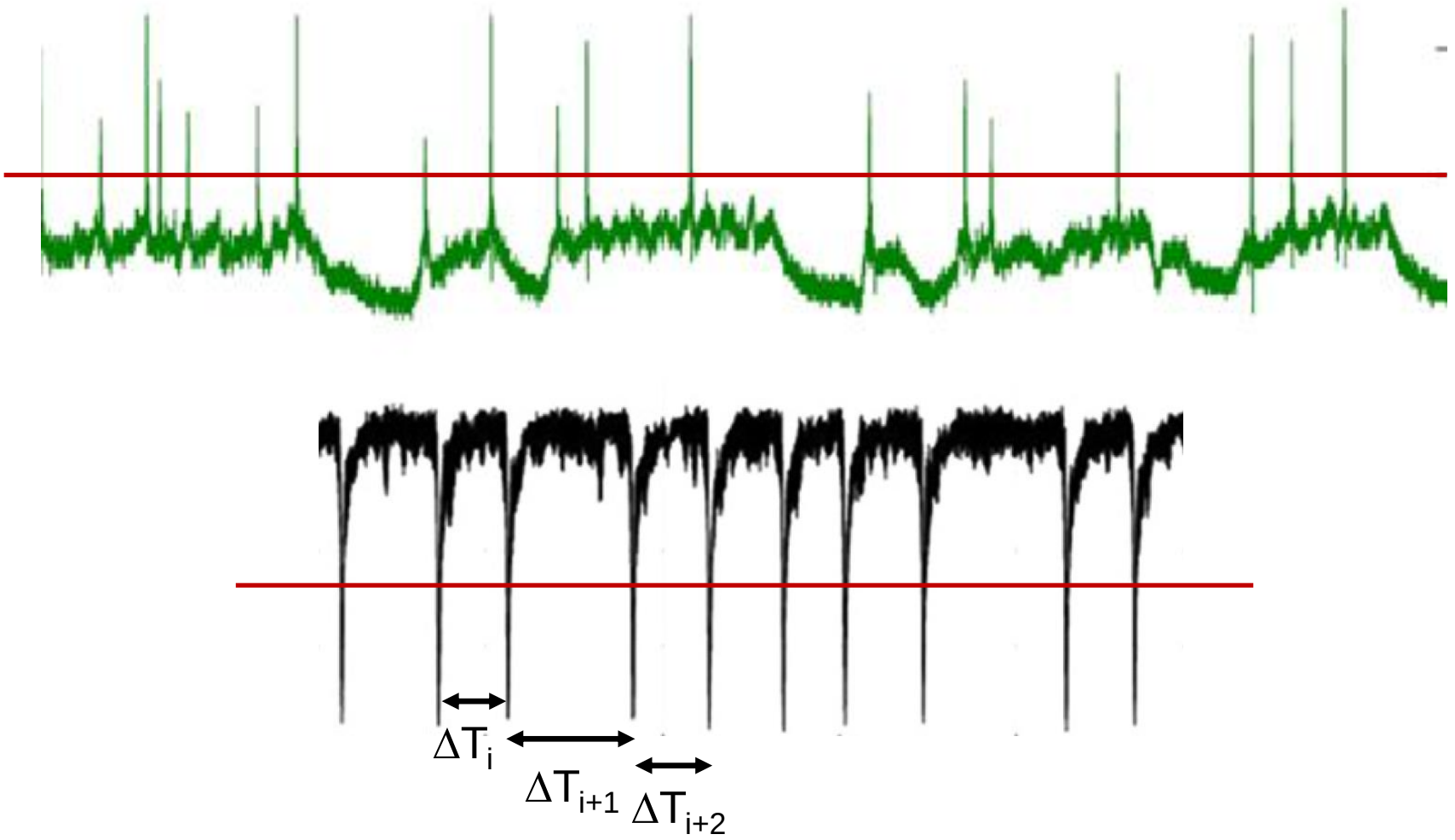
Thresholding detects the spike times ⇒ Point Process ⇒ sequence of inter-spike-intervals (ISIs)



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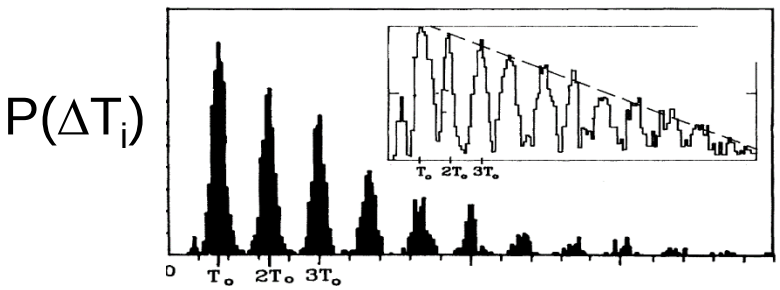
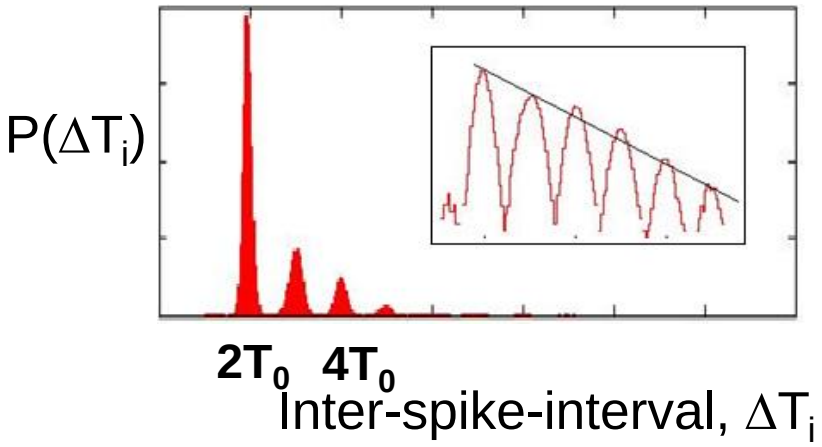
Real neuron ISI distribution

(spikes in the auditory nerve when a monkey hears a pure tone sound)

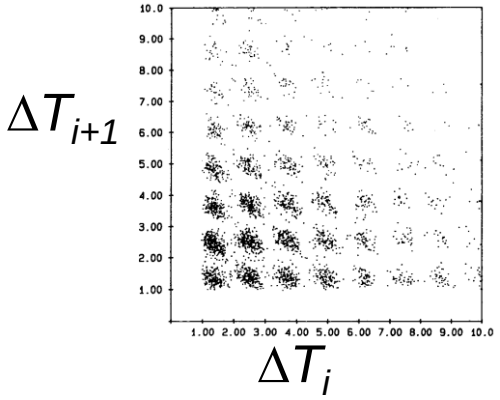


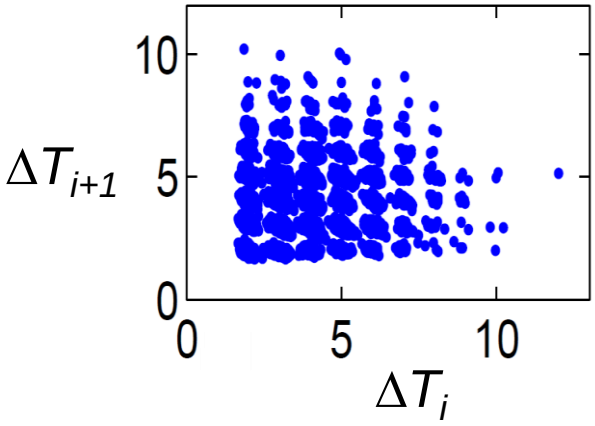
Diode laser ISI distribution

(when the laser is sinusoidally modulated)



Spikes in the auditory nerve when a cat hears a pure tone sound:





How to detect similar temporal order in the ISI sequences?

Andre Longtin et al. PRL (1991), Int. J. Bif. Chaos (1993).

Andres Aragoneses et al. Optics Express (2014).

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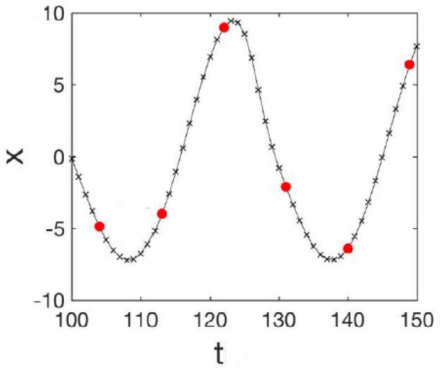
Symbolic analysis method: ordinal analysis

$\{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}$

Possible order relations among three numbers (e.g., 2, 5, 7)

{…2, 5, 7…}	{…5, 2, 7…}	{…7, 2, 5 …}
A, B	C, D	E, F
{…2, 7, 5…}	{…5, 7, 2…}	{…7, 5, 2…}

Which is the code?



A B F C

Drawback! Information about the values is lost.
(5,7,2) and (5,70,2) are both represented by symbol “D”.

C. Bandt and B. Pompe, Phys. Rev. Lett. 88, 174102 (2002).

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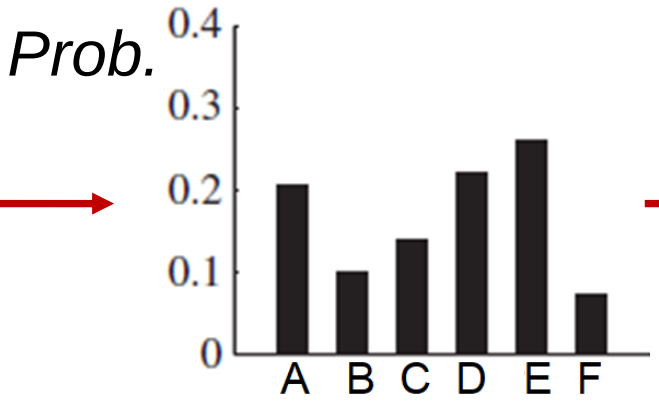
From a sequence of data points, by counting the different patterns we can estimate the "ordinal probabilities"



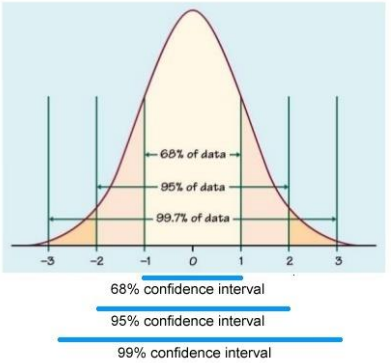
?

What to do next?

Analyze the values of the ordinal probabilities

- **Null hypothesis**: $p_i = p = 1/6$ for all i
- If at least one probability **is not** in the interval $p \pm 3\sigma$ where $\sigma = \sqrt{p(1-p)/N}$ and N the number of patterns:

  We **reject** the NH with 99.74% confidence.
- Else, we **fail to reject** the NH.



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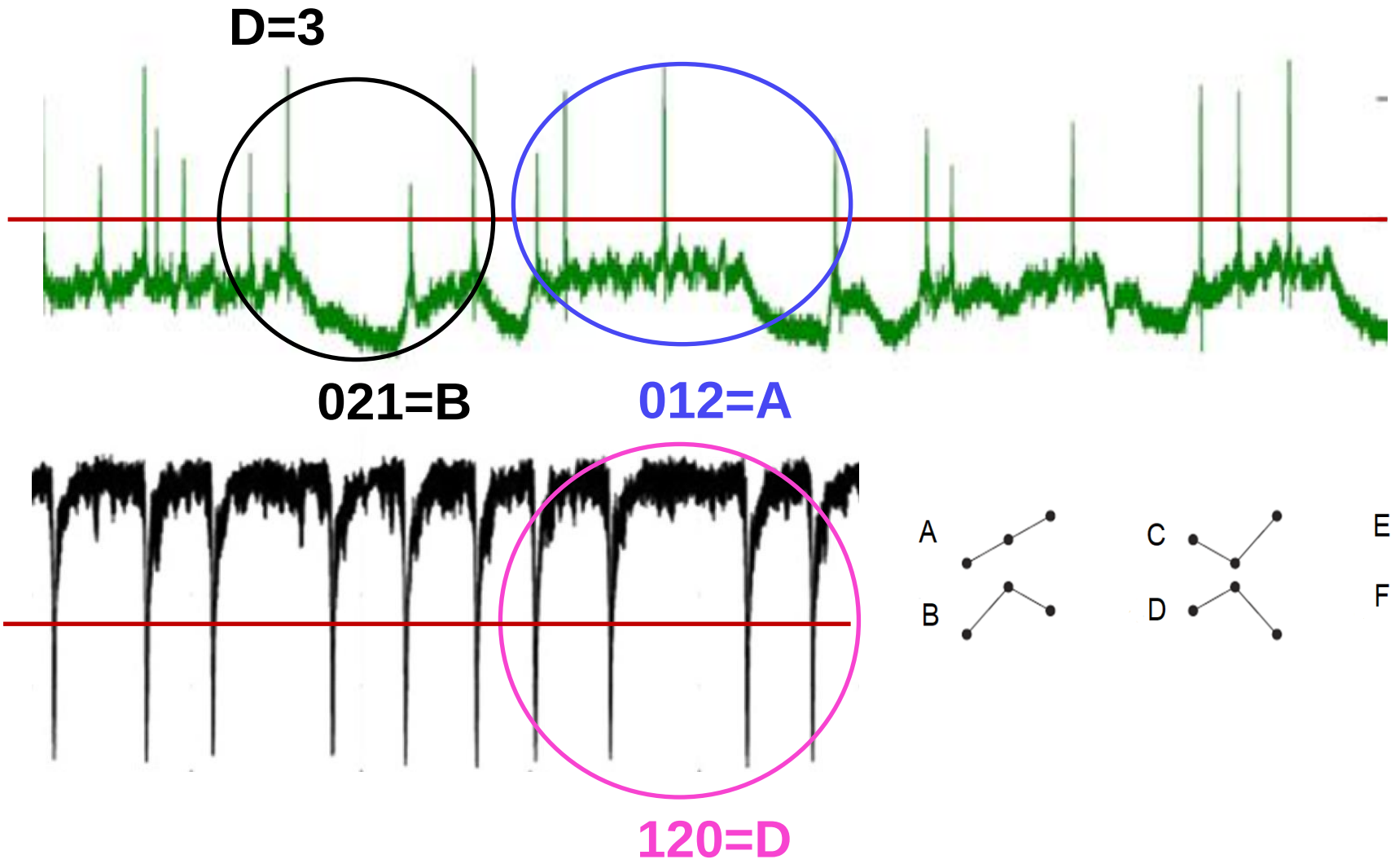
Sequence of inter-spike-intervals (ISIs) ⇒ sequence of ordinal patterns



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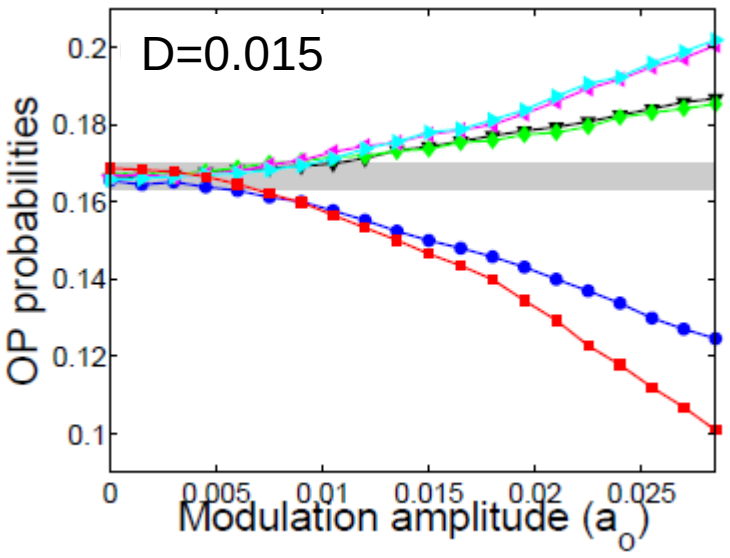
Analysis of spike sequences simulated with a simple neuron model (FitzHugh-Nagumo)

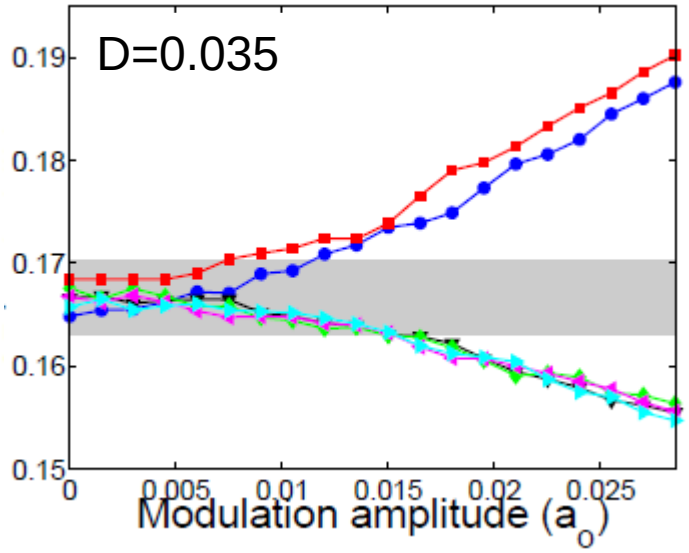
$$\epsilon \frac{dx}{dt} = x - \frac{x^3}{3} - y,$$

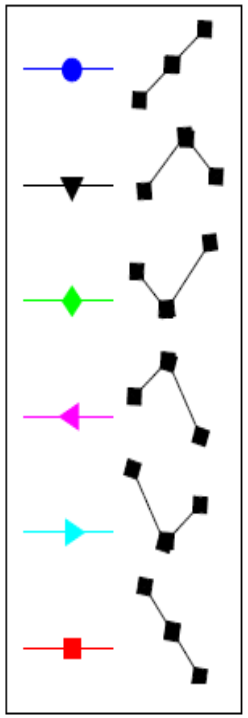
$$\frac{dy}{dt} = x + a + a_o \cos(2\pi t/T) + D\xi(t),$$

Weak, **subthreshold** input

Neural noise
(uncorrelated, Gaussian)







Gray region: NH with 99.74% confidence level

J. A. Reinoso, M. C. Torrent, and C. Masoller, Phys. Rev. E. 94, 032218 (2016).

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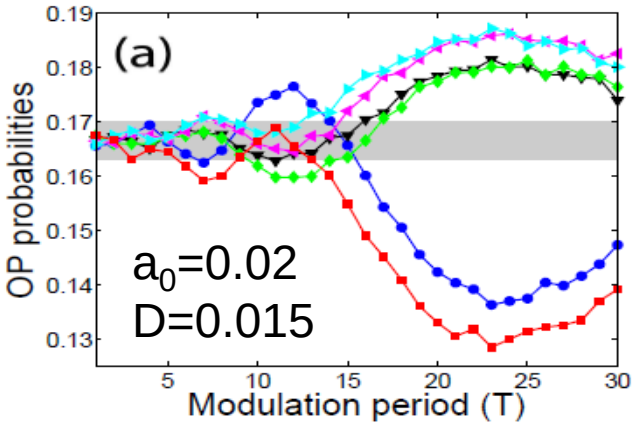
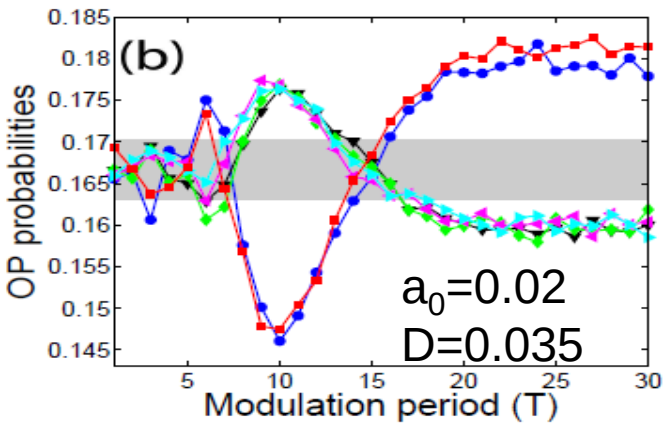
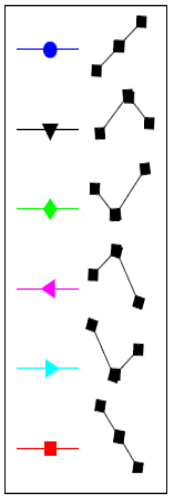
Role of the period of the external input

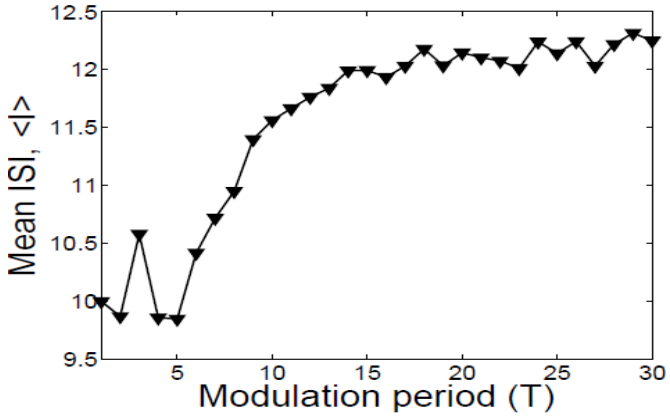


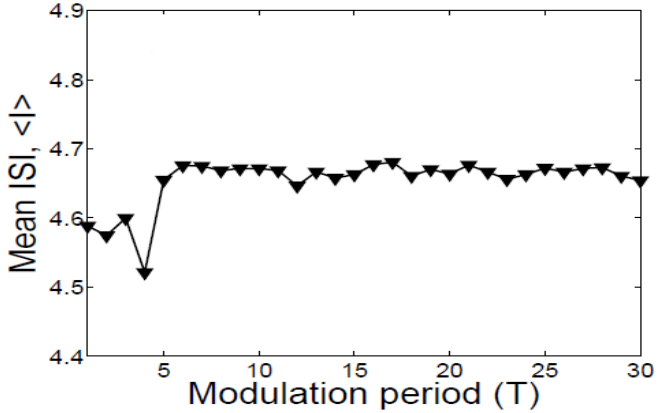




⇒ More probable patterns depend on period and noise strength.

Which is the underlying mechanism? A change of the spike rate?





⇒ No direct relation.

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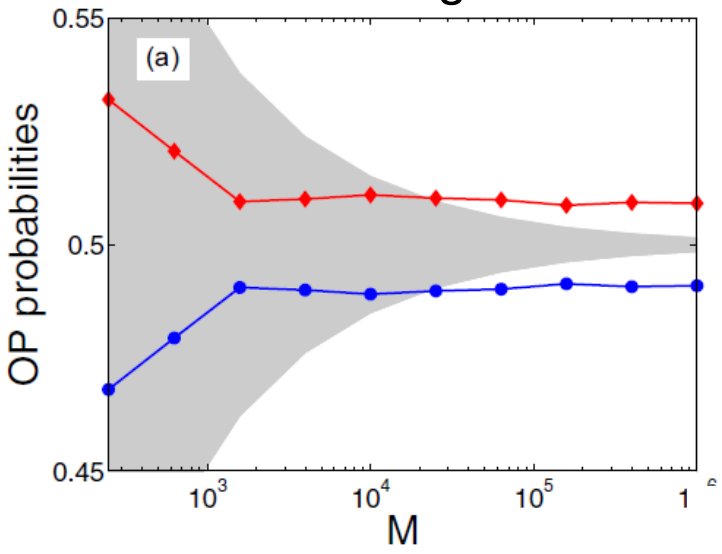
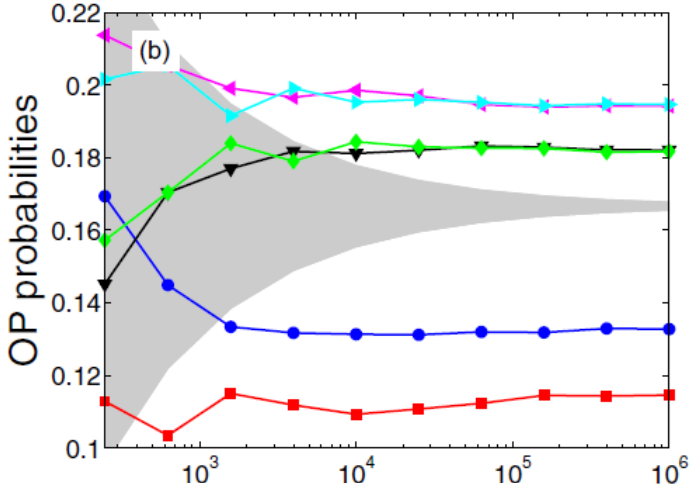
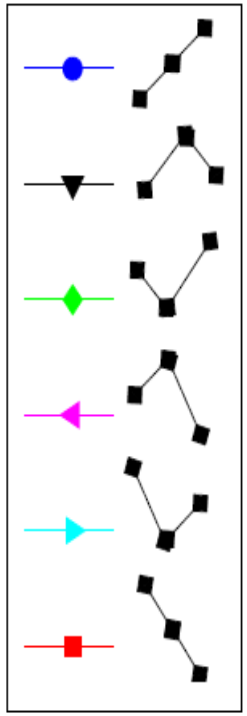
How many spikes do we need to estimate the probabilities?

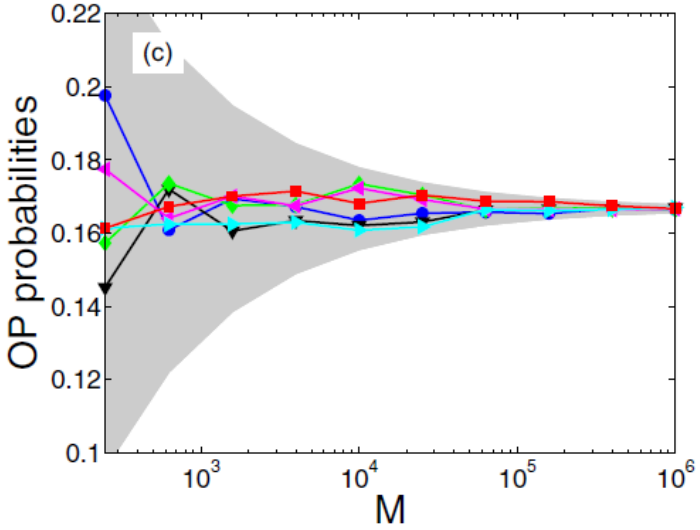
With external signal **01 10**







Without external signal



Gray region: NH with 99.74% confidence level

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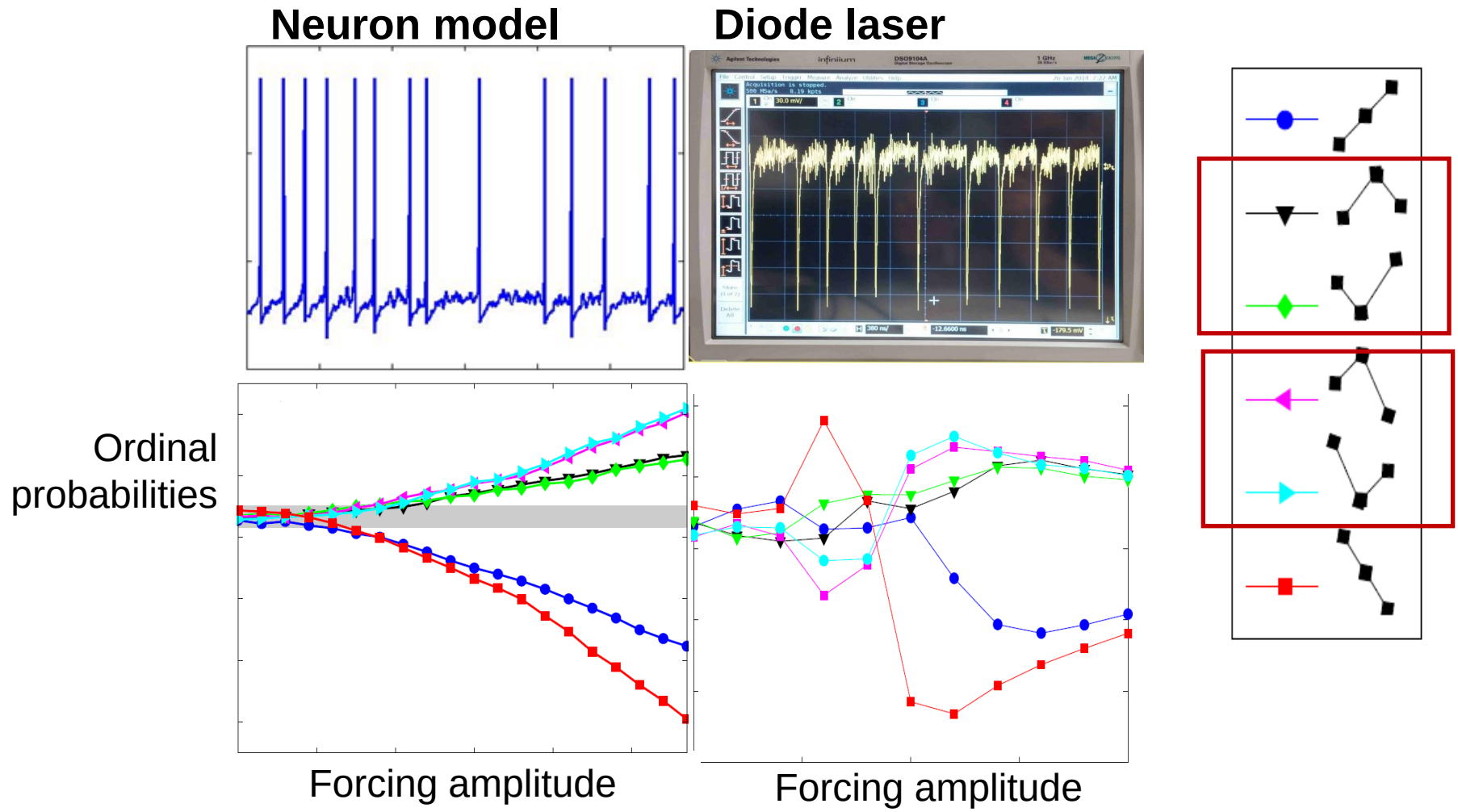
Ordinal probabilities uncover similarities between neuronal spikes and optical spikes



J. M. Aparicio-Reinoso et al PRE 94, 032218 (2016) A. Aragoneses et al, Sci. Rep. **4**, 4696 (2014)

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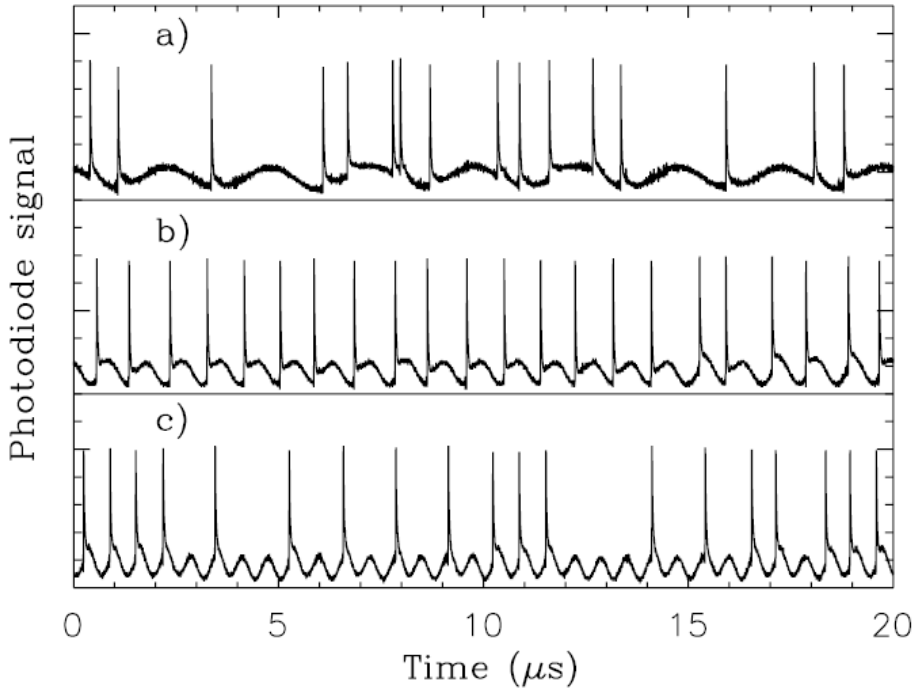
“Stochastic resonance” (SR) has been observed in diode lasers

VOLUME 88, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JANUARY 2002

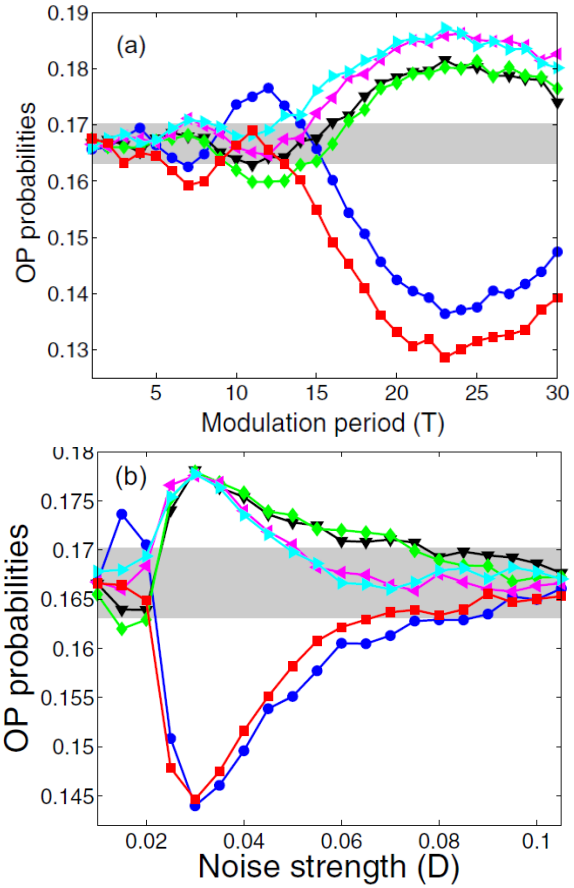
Experimental Evidence of Stochastic Resonance in an Excitable Optical System

Francesco Marino, Massimo Giudici,* Stéphane Barland,† and Salvador Balle
Department de Física Interdisciplinar, Instituto Mediterráneo de Estudios Avanzados (CSIC-UIB), C/ Miquel Marqués 21, E-07190 Esporles, Spain
(Received 1 August 2001; published 10 January 2002)



(varying the frequency of the sinusoidal signal applied to the laser current)

SR also in the neuron model (FitzHugh-Nagumo)



J. M. Aparicio-Reinoso et al. PRE 94, 032218 (2016).

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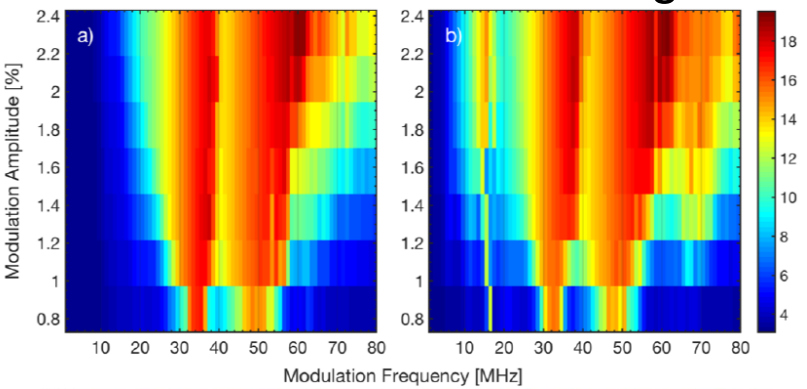
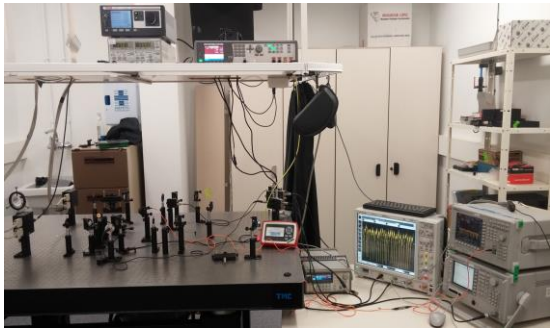
Laser-neuron comparison: a small-amplitude periodic signal encoded in the spike rate

Spike rate in color code

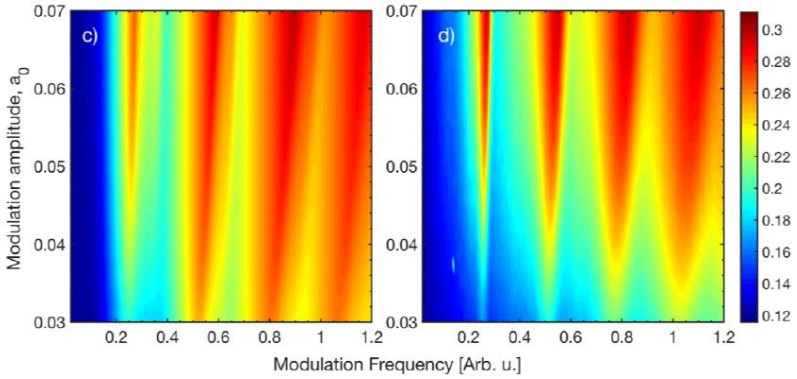
Sinusoidal Pulsed signal

Experiments modulating the laser current





Neuron model with the same input signal



$$\varepsilon \frac{dx}{dt} = x - \frac{x^3}{3} - y\,,$$

$$\frac{dy}{dt} = x + a + D\xi(t)\,.$$

J. Tiana-Alsina, C. Quintero-Quiroz and C. Masoller, "*Comparing the dynamics of periodically forced lasers and neurons*", New J. of Phys. 21, 103039 (2019) (2019).
J. Tiana-Alsina, C. Masoller, "*Time crystal dynamics in a weakly modulated stochastic time delayed system*", Sci. Rep. 12, 4914 (2022).

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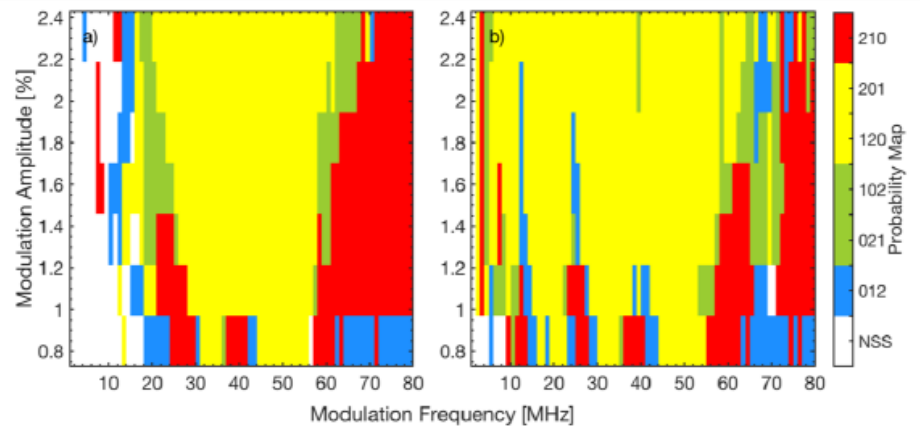
How about the temporal code?

Ordinal analysis uncovers statistical differences in spike timing.

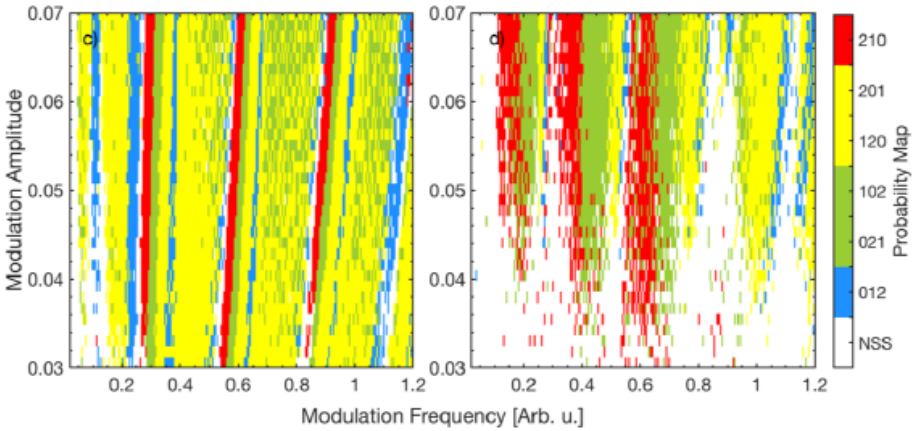
Sinusoidal

Pulsed signal

Diode laser with optical feedback



FitzHugh-Nagumo model



Most probable pattern in color code

J. Tiana-Alsina, C. Quintero-Quiroz and C. Masoller, New J. of Phys. 21, 103039 (2019).

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Single-neuron vs ensemble encoding

- Single-neuron encoding: **slow** because long spike sequences are needed to estimate the ordinal probabilities.
- Ensemble encoding: can be much **faster** because, from the ISI sequences of all the neurons, few spikes per neuron can be enough to accurately estimate the probabilities.

subthreshold input

$$\epsilon \dot{u}_i = u_i - \frac{u_i^3}{3} - v_i + a_0 \cos(2\pi t/T) + \frac{\sigma}{k_i} \sum_j^N a_{ij}(u_j - u_i) + \sqrt{2D}\xi_i(t), \qquad i \neq j$$

$$\dot{v}_i = u_i + a.$$

$$k_i = \sum_j a_{ij}$$

$$a_{ij} = a_{ji} = 1$$
$$a_{ij} = a_{ji} = 0$$

Random with prob. ***p***

M. Masoliver and C. Masoller, "*Neuronal coupling benefits the encoding of weak periodic signals in symbolic spike patterns*", Commun. Nonlinear Sci. Numer. Simulat. 88, 105023 (2020).

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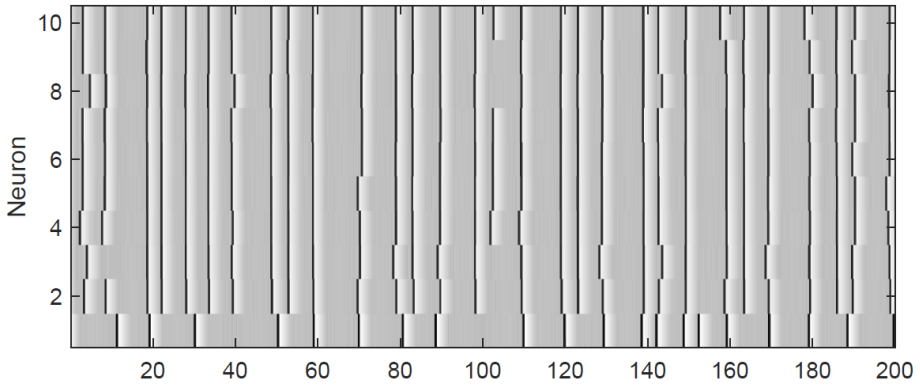
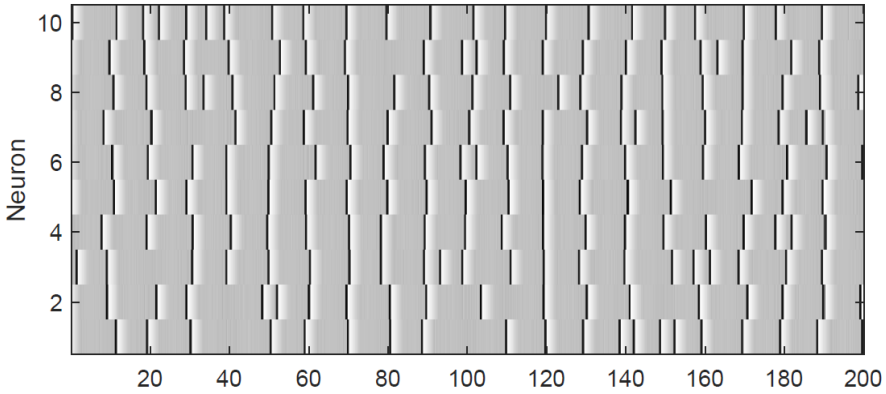
Spiking dynamics with/without coupling, with/without external input

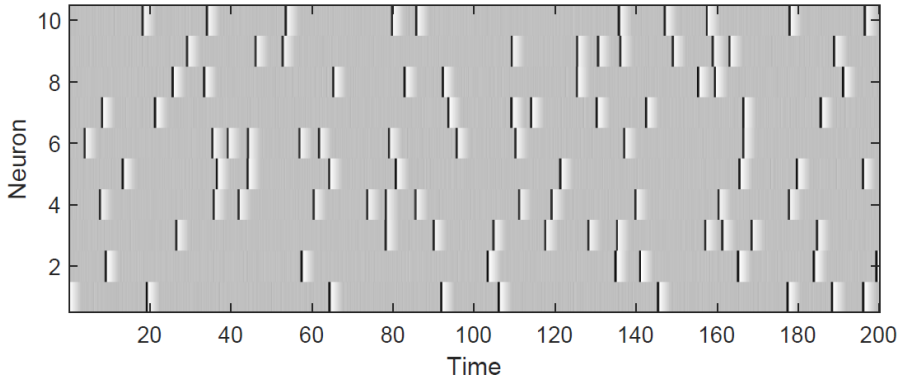
$\sigma \neq 0$
$a \neq 0$



$\sigma = 0$
$a \neq 0$



$\sigma = 0$
$a = 0$



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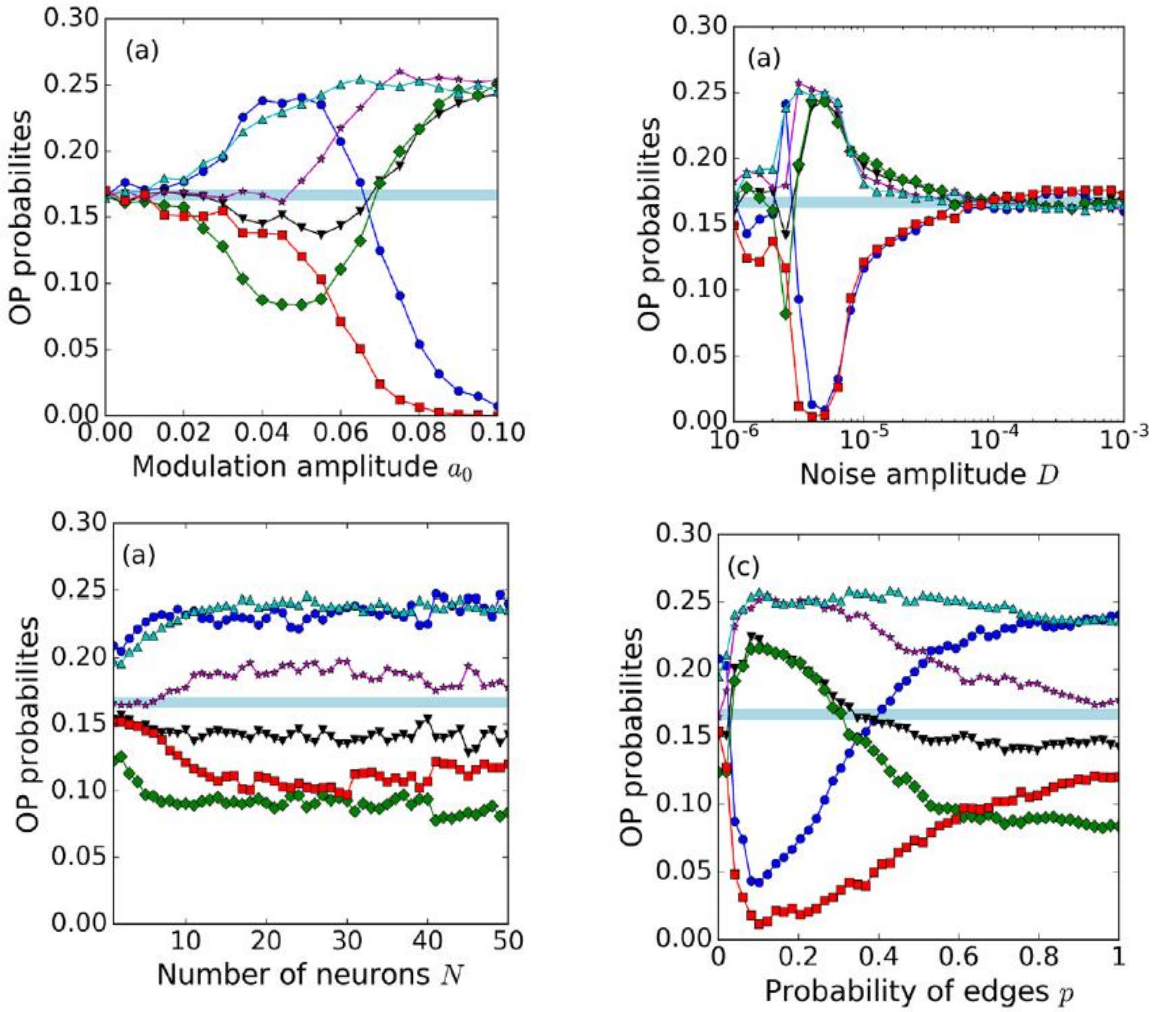
Ensemble encoding of a weak sinusoidal signal in the frequencies of occurrence of ordinal patterns



M. Masoliver and C. Masoller, Commun. Nonlinear Sci. Numer. Simulat. 88, 105023 (2020).

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Take home messages and outlook

- When a neuron perceives a subthreshold sinusoidal input, the ordinal probabilities carry information of the amplitude and period of the input.
- Noise can optimize the encoding of the input.
- The input can not be too slow or too fast.
- A population of neurons can also encode the signal in the probabilities of ordinal patterns.

Ongoing work:

- Can we “decode” the signal’s information?

  Promising results: B. R. R. Boaretto, E. Macau, C. Masoller, “*Characterizing the spike timing of a chaotic laser by using ordinal analysis and machine learning*”, Chaos 34, 043108 (2024)

Thank you for your attention!

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